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RESONANCES AND WAVES IN ONE- AND TWO-ION SPECIES PLASMAS SUBJECTED TO INTENSE MAGNETIC FIELDS

Magne Kristiansen, R. F. Gribble, and W. H. Carter [1963] 21 p

11 refs

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I. Introduction

Resonance effects and waves in two-ion species plasmas subjected to intense magnetic fields have been discussed in some recent papers.[1,2,5,8,11] The experimental results reported in this area to date are very limited in scope.[2,8] Considerable experimental and theoretical investigations remain to be done.

Some of the resonance effects in a two-ion species plasma offer a promising possibility for very effective heating of the plasma. This report will describe in some detail an experimental arrangement presently being built for the purpose of investigating resonance effects and wave propagation in the ion cyclotron and ion-ion hybrid frequency region for one- and two-ion species plasmas.

The principal effects being considered for both theoretical and experimental investigation are as follows:

(1) Power absorption and conditions for optimum power absorption in the indicated frequency region for a two-ion species plasma.

(2) Effects of ion_1-ion_2 collisions on wavelengths and damping

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in a two-ion species plasma.

(3) Power absorption in a "Magnetic Beach" (uniformly decreasing magnetic field region) for a two-ion species plasma.

(4) Polarization measurements of the propagated waves.

(5) Effects on wavelengths, damping and power absorption due to interaction between the plasma sheath and the ions in cyclotron orbit for one- and two-ion species plasmas.

The various modes of propagation in a cold, uniform, one-ion species plasma of infinite extent are widely discussed.[7] In a two-ion species plasma additional hybrid modes occur.[1,5,11] The ones of special interest in this investigation are the lower hybrid frequencies, which Reshotko[5] writes, in the limit of high plasma density, as

$$\omega^2 = \Omega_a^2 \sin^2\theta_{res} + \Omega_e^2 \cos^2\theta_{res} \qquad (1\ a)$$

$$\omega^2 = \frac{\Omega_1^2 + \frac{\Omega_a^2 \Omega_b^2}{\Omega_e^2} \tan^2\theta_{res}}{1 + \frac{\Omega_a^2}{\Omega_e^2} \tan^2\theta_{res}} \qquad (2\ a)$$

For $\theta_{res} = 90^\circ$ these reduce to the electron-ion and ion-ion hybrid resonances of Buchsbaum[1]

$$\omega^2 = \Omega_a^2 = \Omega_e (x_1 \Omega_1 + x_2 \Omega_2) \qquad (1\ b)$$

$$\omega^2 = \Omega_b^2 = \Omega_1 \Omega_2 \frac{x_1 \Omega_2 + x_2 \Omega_1}{x_1 \Omega_1 + x_2 \Omega_2} \qquad (1\ b)$$

where Ω_e = electron cyclotron frequency

Ω_1 = ion cyclotron frequency of ion type 1

Ω_2 = ion cyclotron frequency of ion type 2

x_1 and x_2 are the relative charge concentrations, $x_1 = \frac{Z_1 n_1}{n_e}$ and $x_2 = \frac{Z_2 n_2}{n_e}$.

The resonance described by Eq. (2) is of the "plasma resonance" type in that it is accompanied by a large amplitude of ac space charge field.[1] The ion velocities are large compared to the electron velocities and are 180 degrees out of phase with each other. At resonance even a small amount of collision damping leads to large absorption of the wave energy and a considerable ion heating can be expected.

The initial experimental arrangement is primarily aimed at investigating the frequency range including the ion-ion hybrid frequency and the two ion cyclotron frequencies.

II. Experimental Arrangement

Two different types of plasmas were considered for use in this experiment; one was a hydrogen-deuterium mixture and the other was a mixed alkali metal vapor plasma (e.g. cesium and potassium). At the outset, for practical reasons, it appears advisable to use the hydrogen-deuterium mixture.

The alkali metal vapor plasma poses several technological problems which are somewhat difficult. It will, however, be highly desirable to have such a well-behaved, highly-ionized plasma. Parallel work is therefore being carried out on the development of a suitable alkali metal vapor system. The preliminary design of an alkali metal vapor tube for investigation of one-ion species plasma phenomena, and especially the interaction between the plasma sheath and the ions in cyclotron orbits, is reported here.

The large ac space charge mentioned earlier will tend to shield the electric field which rotates with the ions and is responsible for the energy absorption. To avoid this shielding, one uses a "Stix Coil"[6] to excite the waves and resonances. This coil has alternating sections which are 180 degrees out of phase with each other. It forces oscillations with a finite wavelength. The ions are forced to move alternatingly in and out, and thereby allowing the electrons, which are tied to the magnetic field lines, to flow along the magnetic field and neutralize the space charge. This neutralization has proved to be quite effective, albeit not perfect.

It is, for practical reasons, easier to change the magnetic field than the rf frequency because of the rather complicated tuning process for the rf system. With a fixed frequency of, for instance, 6 Mc/s and a H^+- D^+ plasma, the range to be investigated will then extend from approximately 3,000 to 8,500 gauss, as shown on Fig. 1. The desired magnetic field configuration is as shown in Fig. 2, with a uniform field region around the "Stix Coil" for resonance experiments and with a uniformly decreasing field ("Magnetic Beach") on one side of the coil for wave propagation experiments. A "Magnetic Beach" on both sides of the "Stix Coil" is desirable from the viewpoint of possible reflections of the waves, but would require a much longer magnet coil system.

The general experimental arrangement is shown in Fig. 3 and is

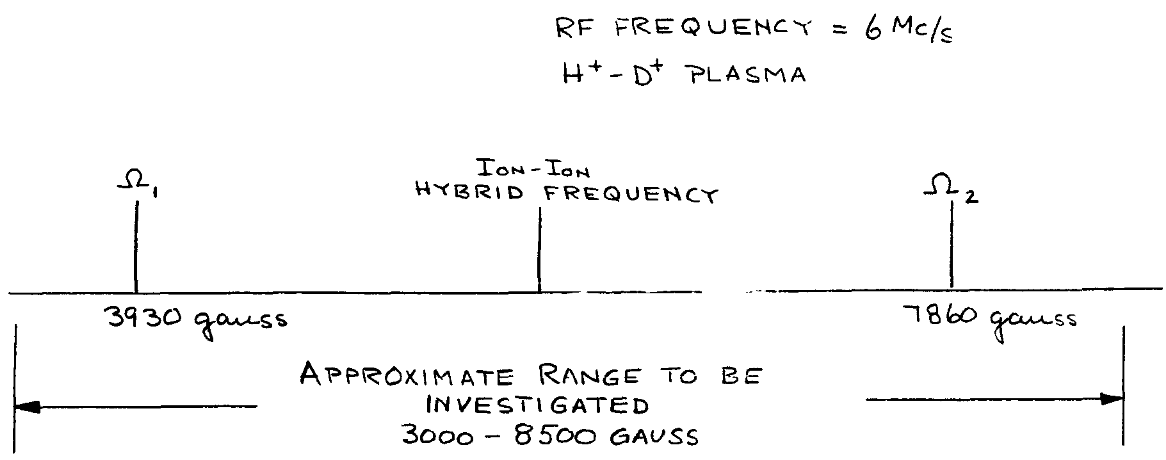


FIG. 1. MAGNETIC FIELD (FREQUENCY) RANGE TO BE INVESTIGATED IN INITIAL EXPERIMENT.

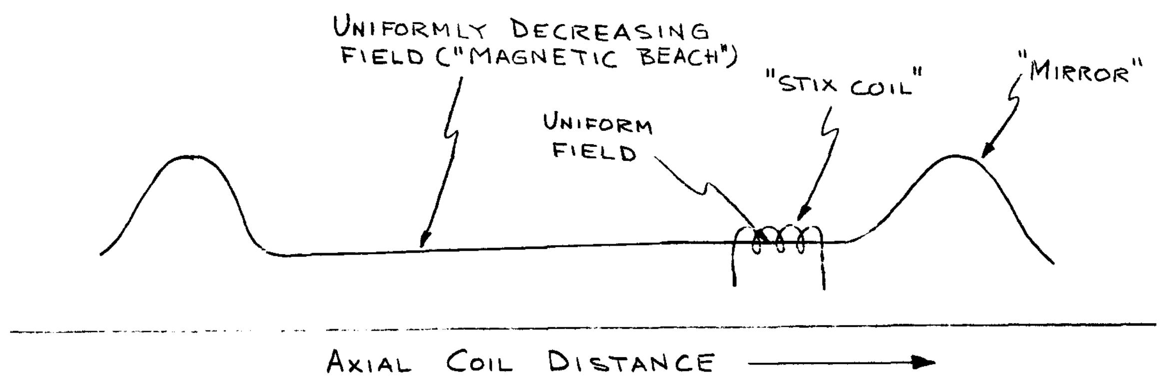


FIG. 2. DESIRED MAGNETIC FIELD CONFIGURATION WITH OFFSET EXCITATION (STIX) COIL.

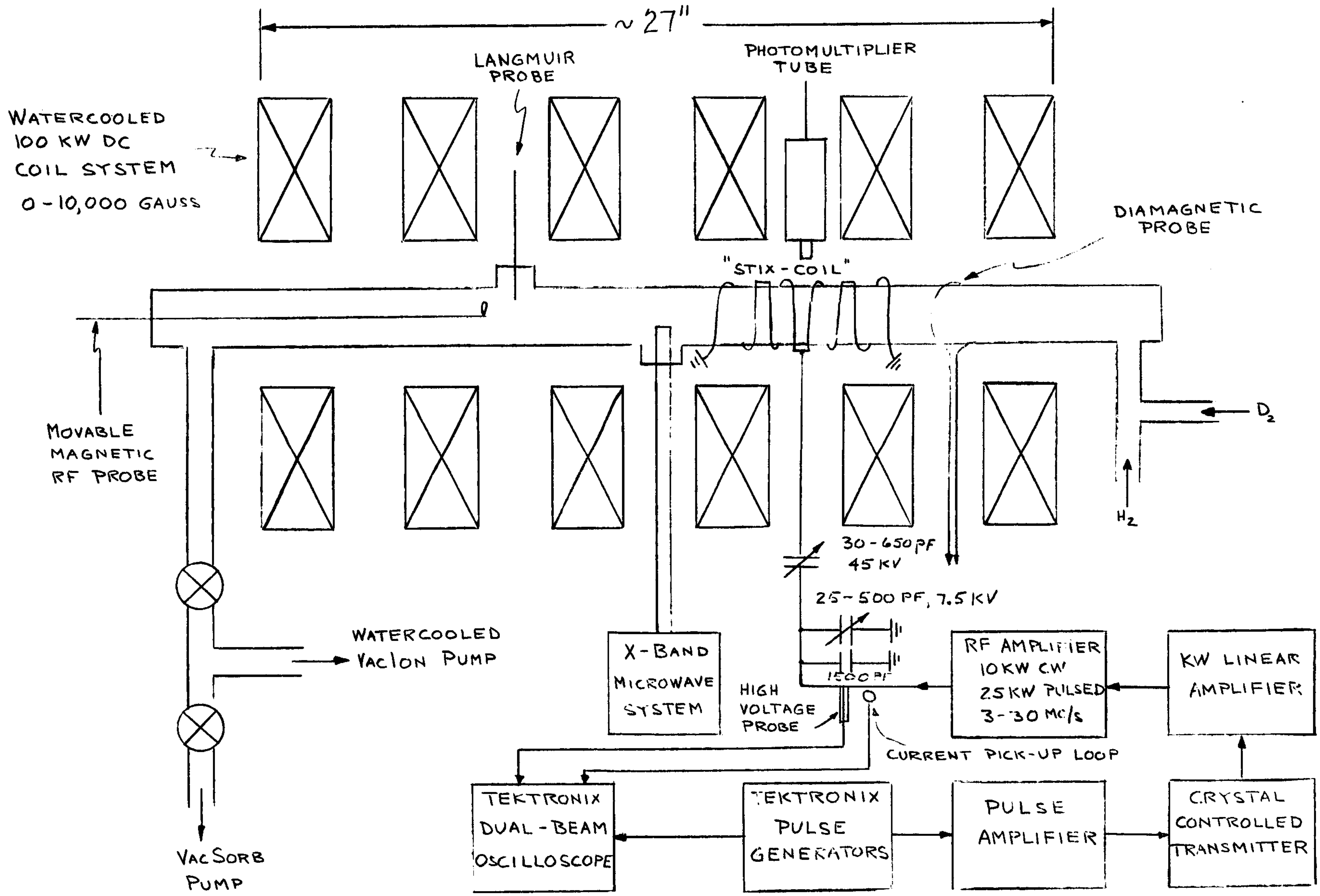


FIG. 3. EXPERIMENTAL ARRANGEMENT

described in the following.

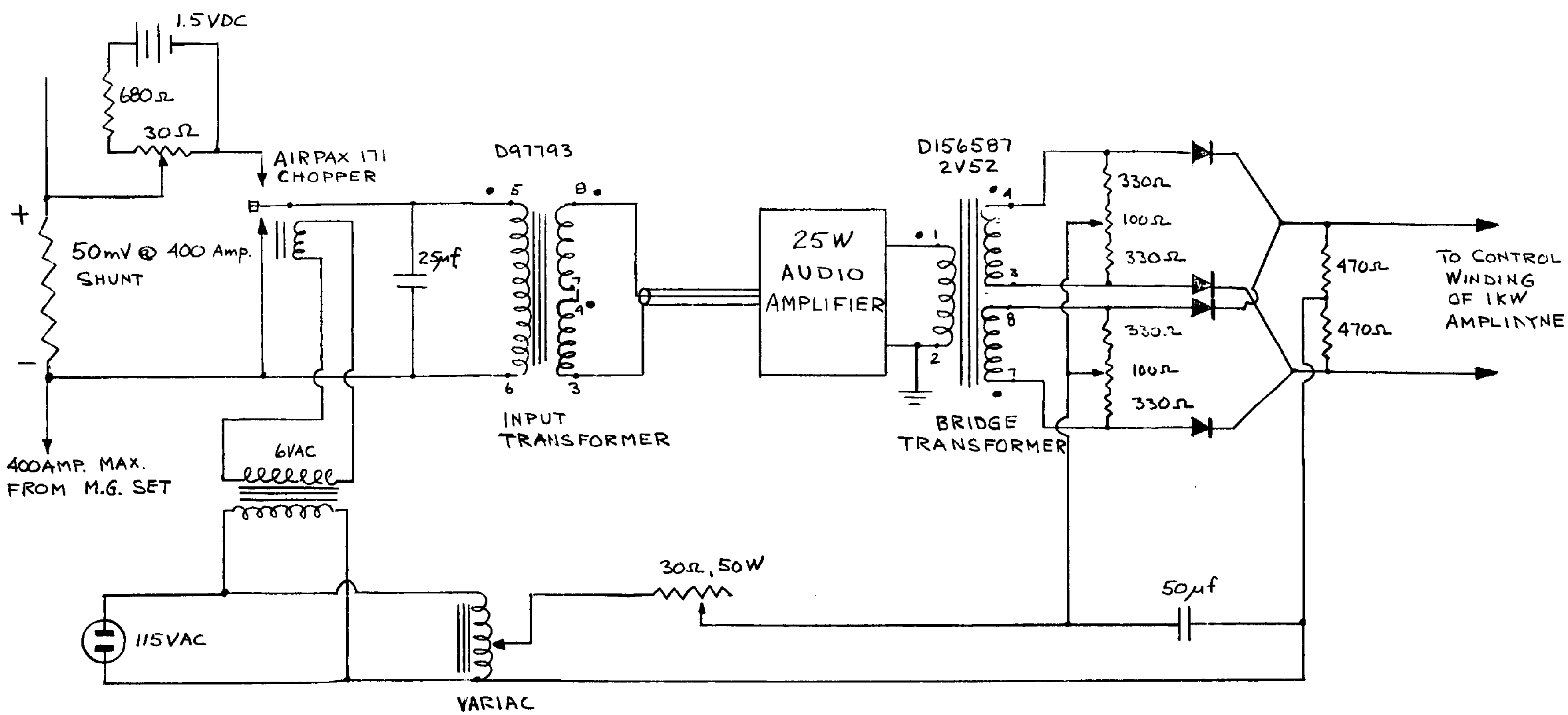
A. Magnetic Field Arrangement

The magnetic field system is a Magnion PF7-275 magnet system with a precision mount, and consisting of six coils. Each coil is 2.8 inches wide and can dissipate 20 KW CW. The spacings between the coils are adjustable so that the desired field configuration can be achieved (Fig. 2). Six coils may not give enough flexibility to obtain a long enough "Magnetic Beach" region, but the system can be expanded to ten coils at a later date.

With one-inch spacing between each coil there is less than 0.1% space ripple in the field. The coils have a 7-inch bore, and with a 2-inch average spacing between the coils the system will be approximately 26.5 inches long. Total available DC power is presently 100 KW (16.6 KW/coil) which will give a magnetic field of up to approximately 10,000 - 11,000 gauss for zero coil spacing and 5,500 - 6,500 gauss for two-inch coil spacing.

Several other coil systems and designs were evaluated, but the Magnion system was chosen because of better characteristics (gauss/KW) and lower cost than any comparable system. The Magnion system is supplied with a convenient pre-aligned precision mount and has an excellent copper packing factor since it is using edge cooling instead of hollow copper conductors.

Power to the coils is supplied by a 100 KW motor-generator set. A control system has been designed for Amplidyne regulation of the generator output current (Fig. 4).



THE AMPLIDYNE DRIVES THE GENERATOR CONTROL FIELD ON THE 100 KW M.G. SET AND THEREBY REGULATES THE OUTPUT CURRENT.

FIG. 4 AMPLIDYNE CONTROL SYSTEM FOR 100 KW MOTOR - GENERATOR SET.

B. RF Excitation System

A 3 KW (10 KW pulsed) oscillator (Fig. 5) has been designed, fabricated, and tested. This oscillator will be used to ionize the plasma. The excitation and wave propagation signal is provided by a modified, commercial, crystal-controlled transmitter driving a KW linear amplifier. The oscillator and the output stage of the crystal controlled transmitter are pulsed by a modified Tektronix pulse generator system.

The 10 KW pulsed oscillator may give a somewhat low fractional ionization of the gas. Therefore, an amplifier which can be pulsed to 20 - 25 KW has been designed (Figs. 6 and 7). This power amplifier and its power supply are presently being assembled. The plate voltage of the amplifier can, if necessary, be doubled for pulsing so that approximately 50 KW pulsed output power can be obtained. The crystal controlled transmitter and the KW linear amplifier will then drive the power amplifier, and the "Stix Coil" will be supplied both ionization and wave generation pulses. The system is first pulsed at maximum output power at the fixed frequency of the transmitter. The power is then lowered for wave generation and power absorption measurements. This is achieved by using two independent pulse generators which pulse the rf system to two different levels (Fig. 8). When the magnetic field is adjusted for resonance, the ionization should be very effective. The plasma can be expected to decay over a period of up to several hundred microseconds, depending upon temperature, density, magnetic field, and neutral gas pressure. The time delay between the two pulses from the pulse generators is

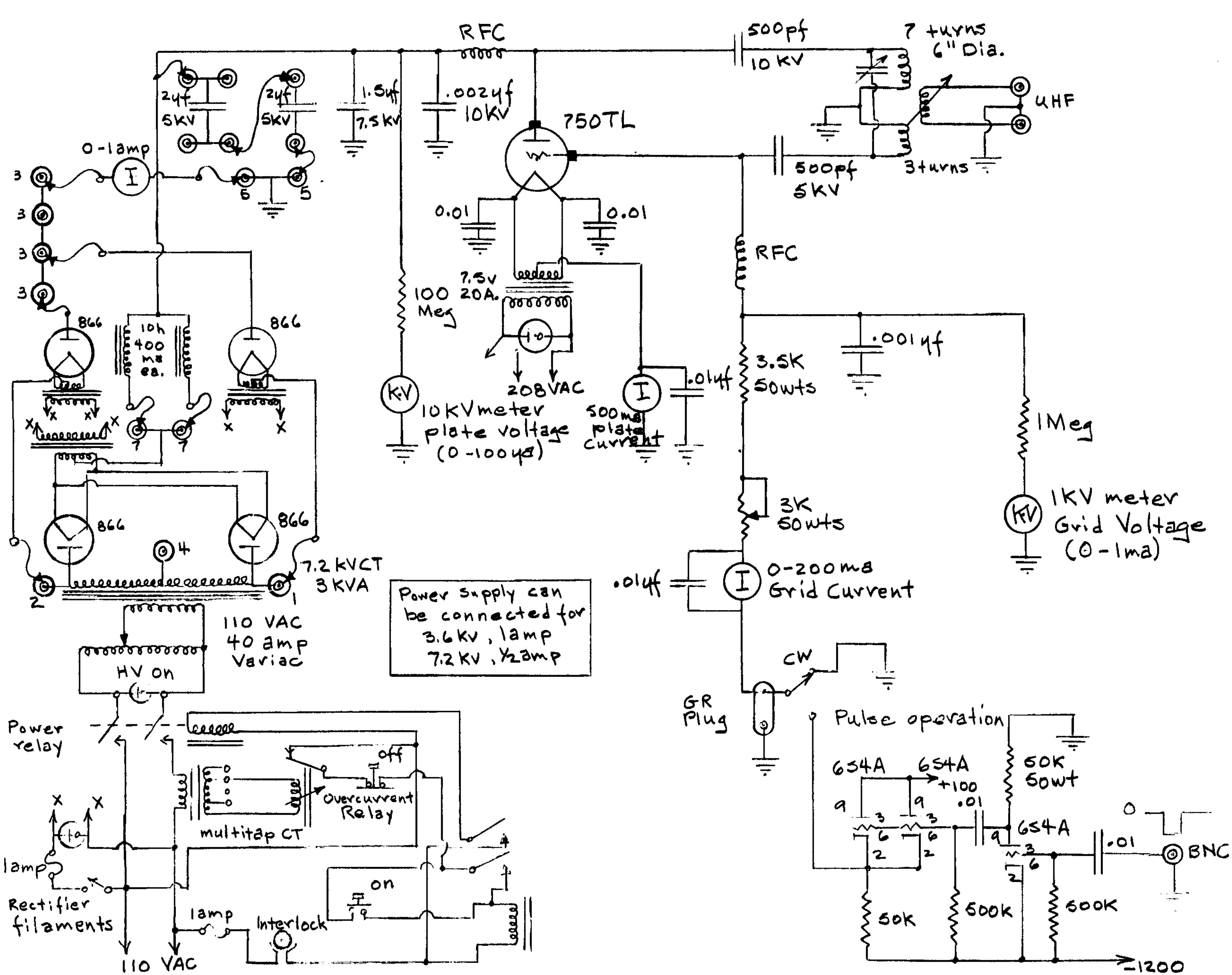


FIG.5 - 3 KW CW OSCILLATOR
(10 KW PULSED)

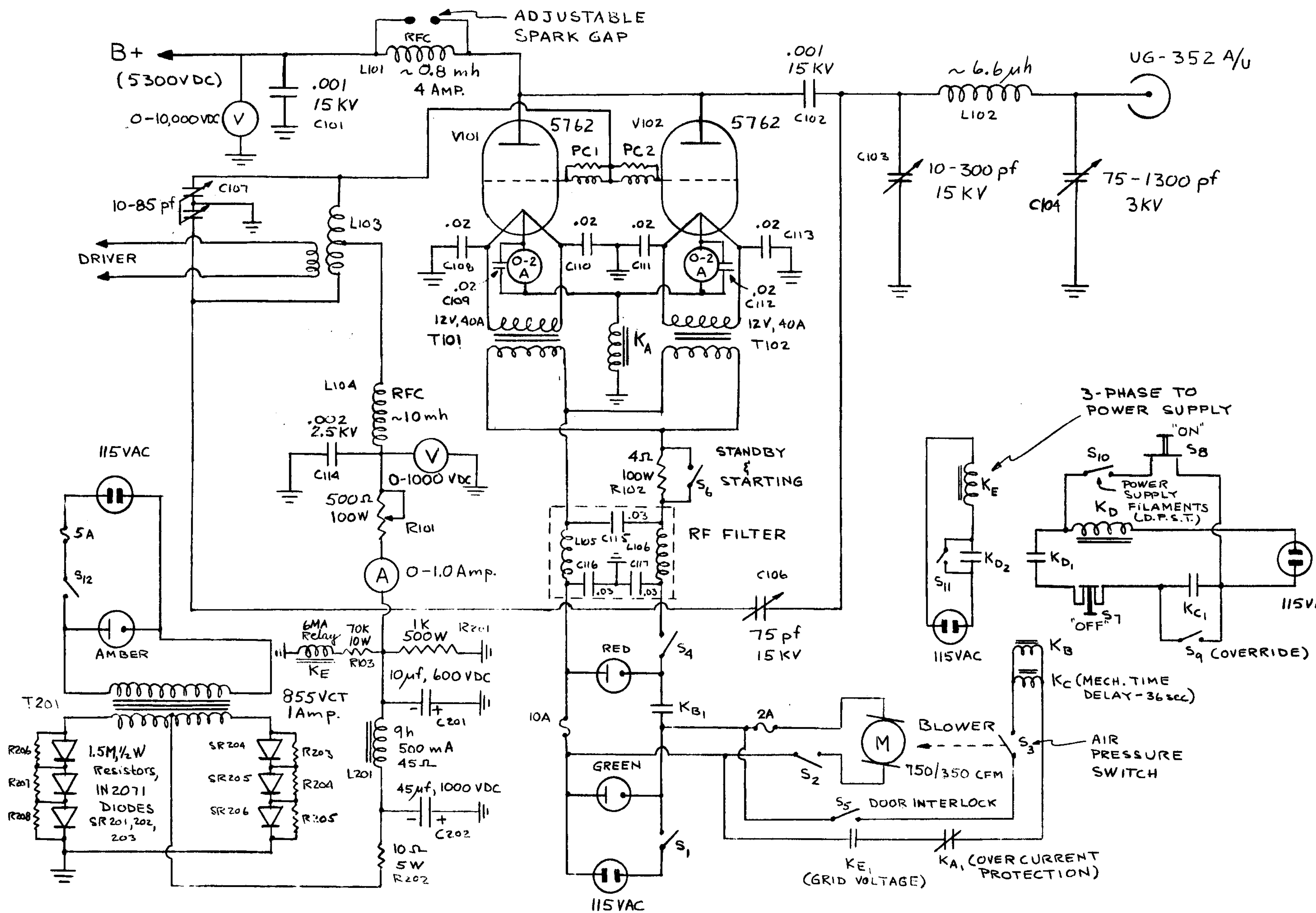
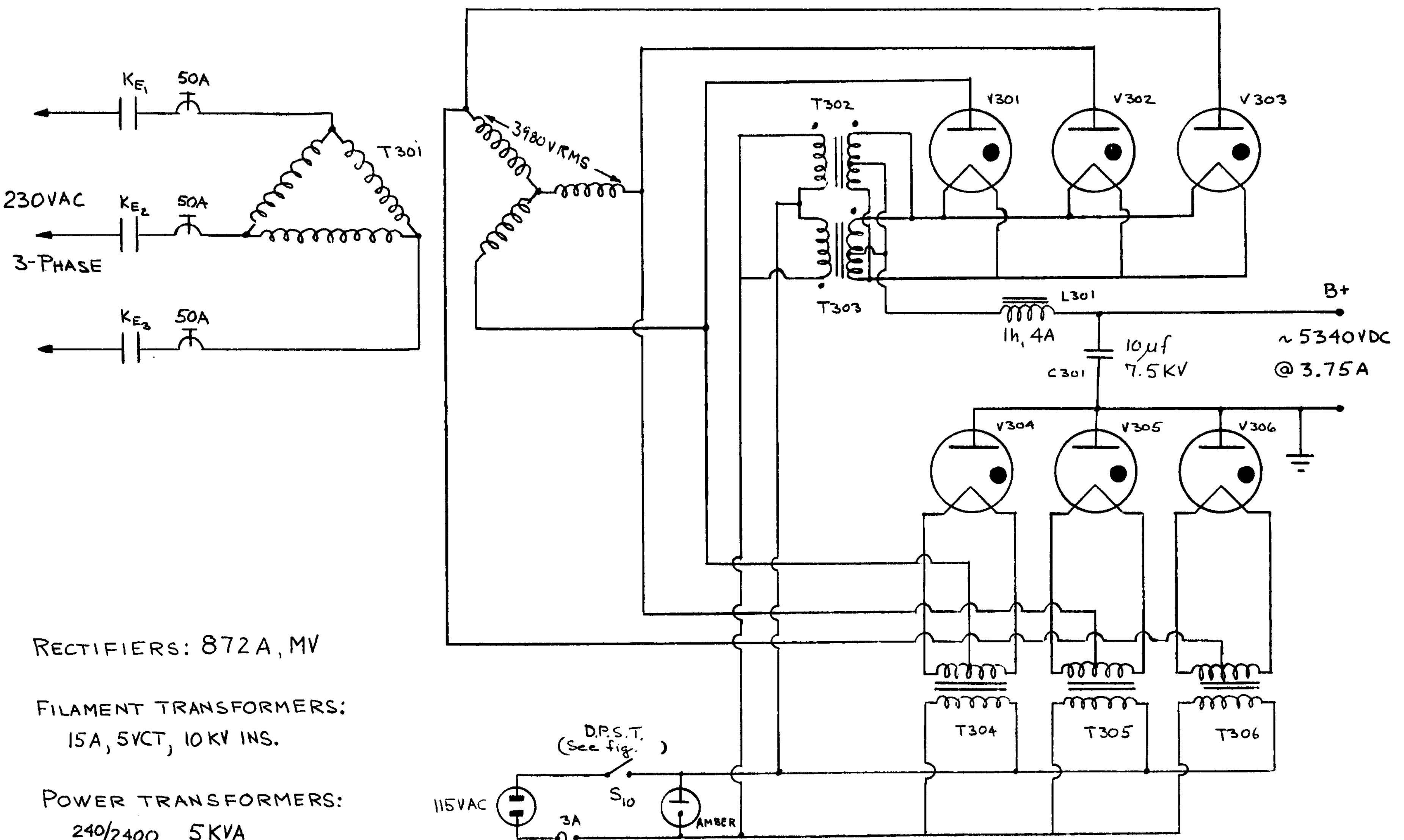


FIG. 6 10KW RF AMPLIFIER (25KW PULSED)



RECTIFIERS: 872A, MV

FILAMENT TRANSFORMERS:
15A, 5VCT, 10KV INS.

POWER TRANSFORMERS:
240/2400, 5KVA

FIG. 7 15 KVA DC POWER SUPPLY

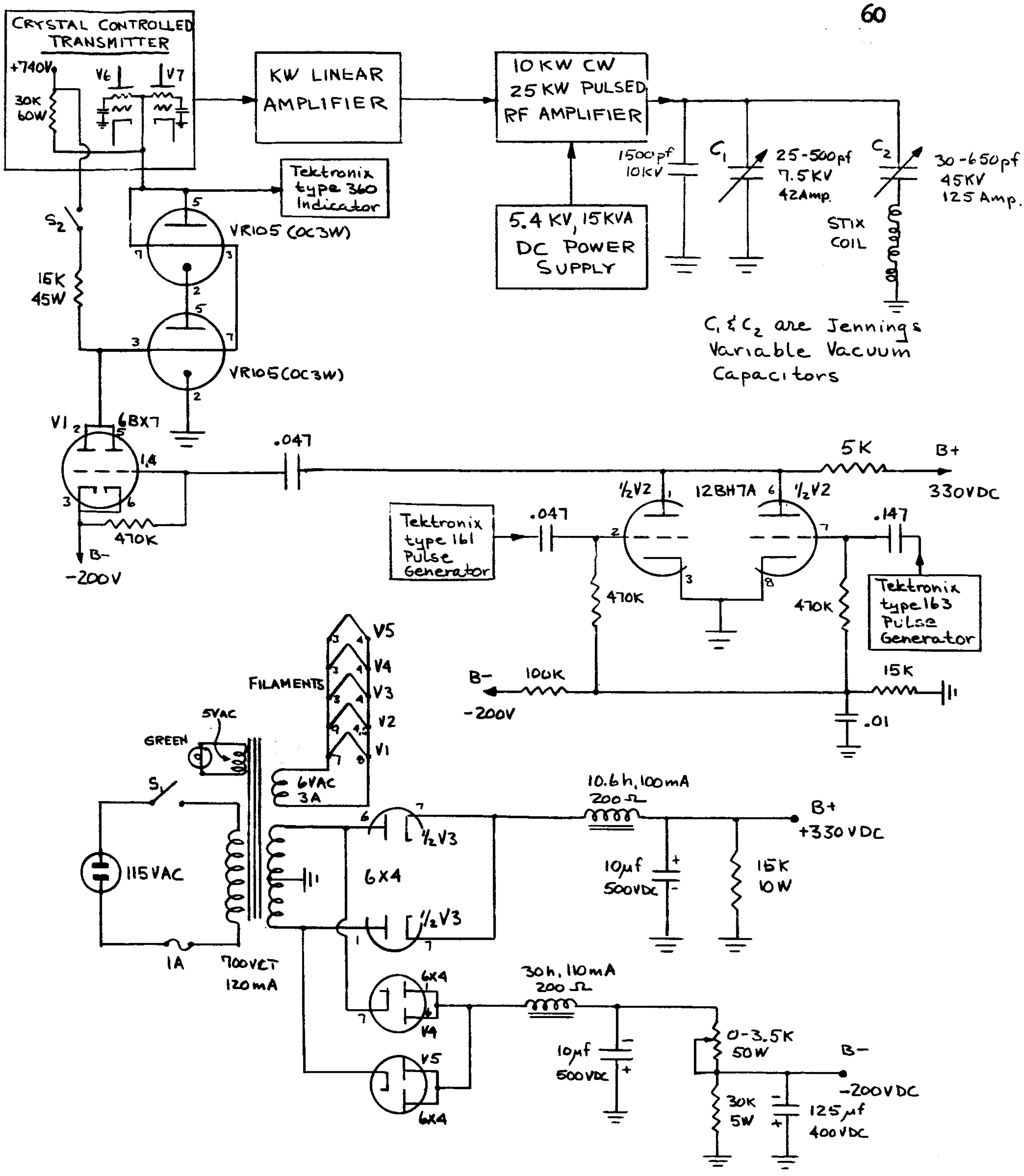


FIG. 8 RF EXCITATION AND PULSE SYSTEM

variable, and the measurements can thus be performed at any desired time in the plasma decay. This allows for a relatively easy way to adjust the plasma density up to a certain maximum given by the maximum obtainable plasma density. The maximum density is difficult to estimate, but quite high densities and fractional ionizations have been obtained with similar arrangements for a one-ion species plasma.[3,4]

The tuning of the rf system and the "Stix Coil" resonance system for most effective wave generation and power input to the plasma is quite tedious. Attention is being given to a simplified tuning process.

C. Vacuum System

1. Hydrogen-Deuterium Gas

The vacuum system is shown on Fig. 9. The plasma tube itself is approximately 1 meter long with a 64 mm diameter. All connecting parts and valves are Varian ultra-high vacuum equipment with ConFlat flanges. Two Granville-Phillips variable leaks are used for admitting the gas into the system. The combination of VacSorb and VacIon pumps gives a very clean system without the usual back diffusion of pump oil. The water-cooled, high throughput VacIon pump was chosen instead of the conventional VacIon pump because of the expected relatively large gas pressure at the pump, which would overheat the regular pump.

The hydrogen and deuterium will be leaked into the system from bottles of pure gas. Also being considered is the possibility of admitting the gases through two carefully controlled, heated, palladium leaks.

2. Alkali Metal Vapor

An alkali metal vapor plasma produced by contact ionization on a hot surface is very desirable from the viewpoint of its quiescent, highly ionized nature. The system must, however, be carefully designed so as not to include materials which react with alkali metal vapors at elevated temperatures.

A design based on Varian parts and operating in the vapor mode has been made for such a plasma system (Fig. 10) and several well-qualified firms have been approached about the possibility of building the critical anode assembly. This system is, in its present design, only well-suited for a one-ion species plasma since the temperature of the coldest place in the tube will determine the vapor pressure of the alkali metal. Therefore, it appears difficult to adjust the relative gas concentrations if two different alkali metals are used in the tube at the same time. The tube seems, however, to be very well-suited for investigating single ion species plasma phenomena, and especially the sheath interaction with ions in the cyclotron orbit.

D. Diagnostics

1. Power Input Measurements

A meaningful quantity to compare and discuss under varying plasma conditions is the "power ratio", W, where

$$W \doteq \frac{\text{Avg. rf power input to the plasma}}{\text{Avg. rf ohmic power loss in coil system}} \qquad (3)$$

W = 3.5 means that 3.5 times as much power goes into the plasma as into the coil system, or that the power transfer efficiency is $\frac{3.5}{3.5+1} \times 100\% \cong 78\%$.

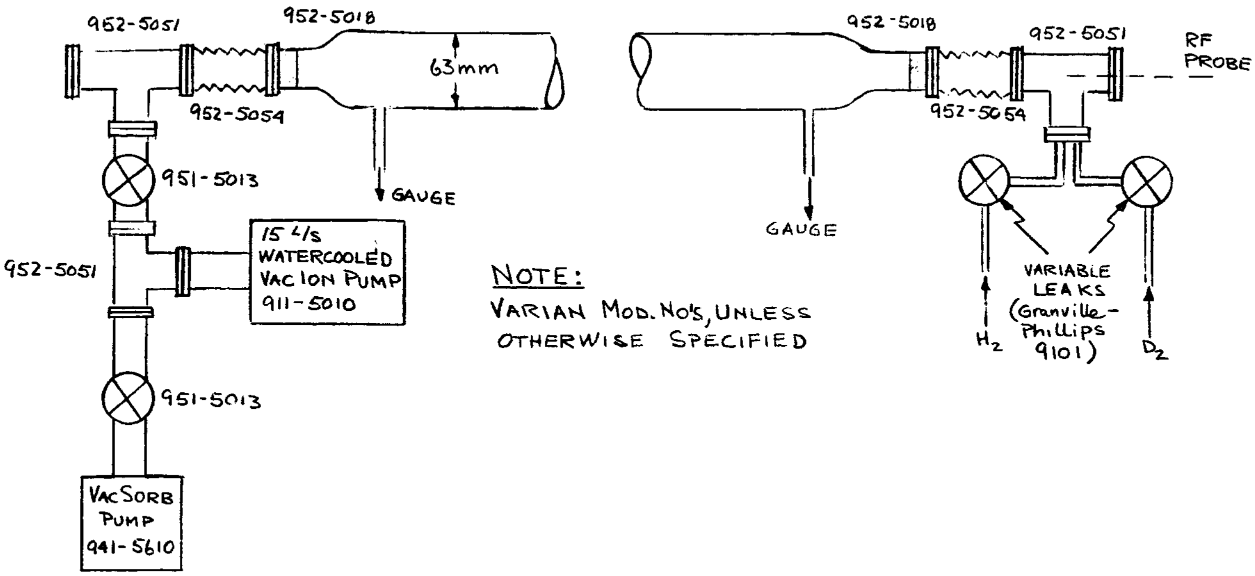
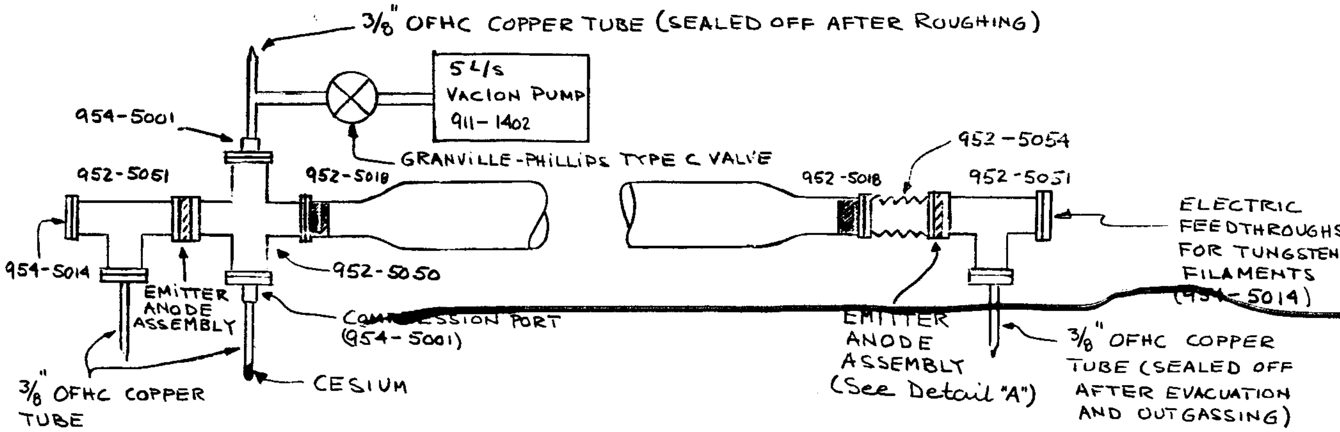
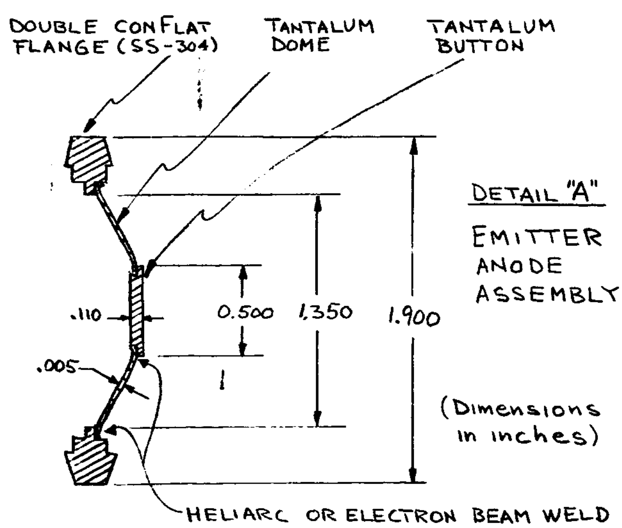


FIG. 9 VACUUM SYSTEM FOR HYDROGEN-DEUTERIUM PLASMA.





NOTE: VARIAN MOD. NO'S

THE EMITTER ANODE ASSEMBLIES ARE VACUUM TIGHT. THE TANTALUM BUTTONS ARE HEATED BY ELECTRON BOMBARDMENT FROM HEATED TUNGSTEN FILAMENTS WHICH ARE KEPT AT 600-1000 VOLT BELOW GROUND POTENTIAL AND SHIELDED FROM THE WALLS OF THE "TEES" (952-5051)

FIG. 10 ALKALI METAL VAPOR PLASMA SYSTEM (BAKEABLE)

The Q of the coil system must therefore be measured in advance so that the coil system loss at the given frequency is known. The system can be further calibrated by placing known resistors across the "Stix Coil".[6]

The input current can be measured by a rf probe under the shielding of the coaxial cable from the rf amplifier. A Tektronix type P 6013 High-Voltage probe is used to measure the input voltage. By displaying these two quantities (I_{in} and V_{in}) simultaneously on a dual-beam oscilloscope one can then measure the phase angle between them. Knowing I_{in} , V_{in} , the phase angle between these two quantities, and the Q of the coil at the operating frequency, one can then calculate the power input to the plasma and the "power ratio", W.

2. Rf Probe Measurements

A single turn rf magnetic probe will be inserted from one end of the plasma tube as indicated in Fig. 4. The probe is shielded and movable in the axial direction as well as having angular freedom. The probe measurements, when properly interpreted, can give information regarding wave length, damping and polarization of the axially propagated wave and the rf field distribution in the tube. By placing the discharge tube at an angle in the magnetic field one can also observe propagation at small angles from the magnetic field vector. (The tube can be placed at approximately 9 1/2 degree angle with respect to the magnetic field.)

The probe should be placed far enough away from the "Stix Coil" to assure that the signal it picks up is from the propagated wave and not from the induction field of the coil.

Some difficulty is anticipated with regard to this last point in the present magnet system with 6 coils.

3. Diamagnetic Probe Measurements

The diamagnetic probe consists of a single or multiloop wire wrapped around the discharge tube and firmly supported from mechanical vibrations. The integrated probe signal will, assuming space charge neutrality, give an indication of plasma density and temperature.

$$\int V dt = \frac{4\pi k}{B_0}\left[n\left(T_{e\perp} + T_{i\perp}\right)\right] \qquad (4)$$

where V = probe signal

B_o = the zero order magnetic field

k = Boltzmann constant

n = $n_i = n_e$ = plasma density

$T_{e\perp}$ = electron temperature, perpendicular to $\vec{B}_o$

$T_{i\perp}$ = ion temperature perpendicular to $\vec{B}_o$

The diamagnetic signal is, however, quite weak and there is still a question as to whether it will be of measurable magnitude in this experiment.

If the plasma density is measured by an independent method one then has an expression for $T_{e\perp} + T_{i\perp}$. The magnitude of the diamagnetic probe signal will also help in studying the power input to the plasma.

4. Density Measurements

X-band (9,000 Mc/s) microwave equipment is available for limited electron temperature and density measurements. The standard microwave techniques that are developed for measuring the electron density of a plasma in terms of the phase shift of the propagated wave will, however, not work unless $\omega > \omega_p$, the plasma frequency. X-band, or 9,000 Mc/s corresponds to a maximum plasma (electron) density of $10^{12} cm^{-3}$.

Higher densities than $10^{12} cm^{-3}$ are anticipated for parts of the experiment, and several methods are being considered for extending the plasma density measurements.

One may be able to compare the microwave measurements with Langmuir probe measurements at lower densities and then extend the probe measurements to higher densities. The interpretation of the probe signal is, however, very much complicated by the presence of a strong magnetic field and may thus not be practical in this case.

Another possibility is to use the method developed by S. Takeda and T. Tsukishima.[9,10] They determine the electron density by measuring the phase angle of the reflection coefficient at a sharp plasma boundary at X-band frequencies. It will, however, be difficult to arrange the waveguide probe so as to obtain the required sharp plasma boundary. An unpublished paper by Dr. Takeda discusses some of the problems involved.

5. Other

Measurements of the light intensity of the H_β or D_β line in the region under the "Stix Coil" may give valuable information regarding the degree of ionization at any given time during the ionization and wave generation process. The light intensity can be measured by using narrow band interference filters and photomultiplier tubes.

The available microwave equipment (X-band) may also be used for noise measurements from the plasma. From these measurements the electron temperature can be determined if it is sufficiently high (depending on equipment sensitivity).

Plan for the Next Period

During the next period, the research equipment remaining to be fabricated and tested is to be completed. The initial experiments are concerned with ion cyclotron resonances, and effects of ion_1 - ion_2 collisions on wavelengths and damping in two ion species plasma. An experimental investigation of ion interaction with the plasma sheath in a single ion species plasma is to be initiated. Further theoretical studies are to be undertaken in support of the experimental work on these topics.

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